# LITHIUM ION BATTERIES FOR MARS EXPLORATION MISSIONS

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## ABSTRACT

The upcoming NASA's missions aimed at exploring our Planetary system require batteries that can operate at **extreme operating temperatures**, with **high specific energy** and energy densities. Conventional aerospace rechargeable battery systems are inadequate to meet the demands. **Lithium ion rechargeable batteries** are thus being chosen for these missions. The **Mars 2001** (Mars Surveyor Program MSP 01) **Lander** and the **2003 Mars Sample Return / Athena Rover** are among the first of NASA's missions to utilize the lithium ion technology. One common feature of these two missions is the need for the battery to operate well at sub-zero temperatures (down to –30°C), at moderate rates of charge and discharge. Research studies at JPL and elsewhere are therefore focussing on improving the **low temperature performance** of Li ion cells. Preliminary evaluations of the prototype cells reveal the adequacy of their performance to the needs of these missions.

## 1.0 INTRODUCTION

In its pursuit for an improved understanding of the evolution and formation of universe, galaxies, stars, and planets, for the detection of extra-terrestrial life and for establishing a permanent human presence in space, NASA has plans for a number of robotic missions with focused science and with fast turn-around times in the next millennium. Some of these programs/missions include Mars 2001, 2003 Sample Return Mission and follow-on missions, Europa Orbiter, Pluto Kuiper Express, and Solar Probe. These missions employ small to medium size orbiters, probes, landers, rovers, and penetrators for the exploration of the solar system. These spacecraft have stringent performance, weight and environ-mental requirements, which translate into a set of specific and demanding battery requirements (Table 1).

| | LANDERS | ROVERS | GEO | LEO/ PLA. ORBITER | S/C TOOLS | LIBRATION POINT S/C |
|---|---|---|---|---|---|---|
| CAPACITY (Ah) | 20-40 | 5-10 | 10, 20, 35 | 10, 20, 35 | 3-5 AH | 20-25 AH |
| VOLTAGE (V) | 28 | 28 | 28-100 | 28 | 28 | 28 |
| DIS. RATE | C/5-1C | C/5-C/2 | C/2 | C/2-C | C/2 | C/2 |
| CYCLE LIFE | > 500 (>60%DOD) | >500 (>60% DOD) | 2000 (>75% DOD) | >30,000 (>30% DOD) | >100 | 50 |
| OPER. TEMP, °C | -40 to 40 | -40 to 40 | -5 to 30 | -5 to 0 | 0-50C | 25-30 |
| SP. ENERGY (Wh/Kg) | >100 | >100 | >100 | >100 | >100 | 100 |
| EN. DENSITY (Wh/l)* | 120-160 | 120-160 | 120-160 | 120-160 | >80 | 120-160 |

Table 1: Requirements of rechargeable batteries for NASA applications.

For example, some of these missions require batteries that can a) operate at ultra low temperatures in the range of -20 to -100 C (probes, landers, rovers and penetrators), b) withstand extreme shocks of about 80,000 G (penetrators), and c) provide exceptionally long cycle life capability (orbiters). In addition, these requirements dictate that the batteries are lightweight and compact.

## 2.0 MARS PATHFINDER MISSION

Historically, alkaline rechargeable battery systems have been the workhorses for many of NASA's applications described above. For example, nickel-cadmium and more recently nickel hydrogen have been the preferred choice for the applications requiring long cycle life, e.g., LEO and GEO satellites and Planetary Orbiters. However, for the Planetary Landers and Rovers, the mass and volume constraints are becoming crucial such that nickel systems would not meet the mission needs. For example, in a recently successful Mars Lander (Mars Pathfinder) mission, the Entry Descent and Landing (EDL) operations required the battery to provide 1100 Wh, with mass and volume not exceeding approximately 15 kg and 8.8 liters, respectively. These requirements translate into a minimum specific energy of 73 Wh/kg and energy density of 122 Wh/l, which ruled out consideration of both Ni-Cd and Ni-$H_2$ batteries. In addition to the weight and volume limits, the small area of the Lander solar array dictated the selection of a battery with high charge efficiency. Additional mission requirements include : 1) inverted launch, 2) 40 operational cycles, 3) fourteen month total wet stand, 4) high rate pulse capability for pyro-firing, and 5) no electrolyte leakage.

In retrospect, a lithium ion battery would have probably been a better choice. However, due to its non-availability at the time of Mars Pathfinder, a silver-zinc rechargeable battery was selected. The MPF Ag-Zn battery (27 V and 40 Ah) from BST had unique design features such as 1) robust separator system, 2) minimal free electrolyte, 3) large cell plate area, and 4) special vent valves. The cells were housed in a titanium battery case and cover to minimize weight and meet vibration and shock requirements. The battery was provided with a heater system and a thermal battery to maintain the system at least 15°C to enable efficient charging and to augment the battery during pyro-pulses, respectively. The MPF Lander battery performed satisfactorily and met the mission needs during pre-launch, cruise, entry descent and landing (EDL), and primary mission (Sol 1-Sol 30).[1] In addition, it also supported an extended mission from Sol 31-Sol 84. The battery showed a capacity of 55 Ah in the pre-launch discharge. During the cruise period, the battery was held under open circuit at ~ 80% state-of-charge and at -5 to 0°C. The battery supported all the loads during entry, descent and landing operations (maximum load 4.5 A) successfully. The primary mission consisted of thirty days of operation on Mars, during which the battery was called upon to provide thirty charge/discharge cycles with a nominal discharge current of 1 A and an average discharge duration of 16 hours. The typical charge duration was 6-8 hours at a maximum current of 3.5 A. The performance of the battery during Sol-1discharge is given in Fig. 1.

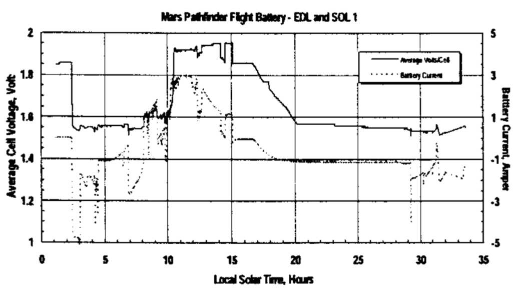


Fig. 1 Performance of Ag-Zn Mars Pathfinder flight battery on Sol-1.

After the successful completion of the primary mission, the mission was effectively extended, due to prolonged battery life. During this phase, the battery loads were significantly reduced to obtain an additional sixty cycles.

Although the batteries lasted longer than 30 cycles and fulfilled the primary mission, the batteries were perceived as being ultimately responsible for ending the mission. During the battery development phase of the program, we encountered problems related to float charge (vented design), electrolyte leakage and sensitivity to orientation. In addition, the wet life and the cycle life, especially after extended storage have been causes for concern in the battery development.

The Pathfinder Rover (Sojourner) contained primary lithium batteries, lithium-thionyl chloride. Their performance had certainly contributed to the success of the mission, yet the batteries prevented nighttime experiment operation after Sol-56. In retrospect, a lithium ion battery, if available, might have extended these missions several fold.

## 3.0 MARS LANDER/ROVER (2001/ 2003)

In the upcoming Mars Lander and Rover missions, there is a greater emphasis on the low temperature performance. The batteries need to perform well down to -30°C, at moderate rates of charge and discharge. Combining the latter with the need for high specific energy of over 100 Wh/kg and energy density of over 150 Wh/l, the lithium ion batteries emerge as the unique choice for these applications. Based on detailed testing of prototype cells from different manufacturers, both NASA and its industrial partner Lockheed Martin Astronautics have chosen lithium ion battery for the upcoming NASA missions, e.g., for the 2001 Lander mission. Likewise, JPL is forging ahead with the plans of incorporating lithium ion technology in the 2003 Sample Return Athena Rover missions. In addition, the follow on missions, in 2005, 2007 and 2009 would be among NASA's missions to utilize lithium ion batteries.

The MSP 01 Lander requires two lithium ion batteries, each of 28 V (eight cells), 25 Ah and 8 kg . An important feature is the ability to operate (both charge and discharge) at continuous rate of C/5 at low temperatures down to -20°C, with a capacity of 80 % of the room temperature value. The typical discharge drains will be C/5 to a maximum of 50% DOD. A single battery can mostly fulfil the needs of the entire mission; the second battery may thus be viewed as back up. However, with both the batteries being connected I parallel (with a diode protection), the actual depths of discharge could be even lower than 50%. Each of the batteries have an independent charge-control unit, with individual cell bypass features for charge control. The maximum charge current will be around 5 A (C/5). The batteries need to provide pulses of about 20 A at 10°C during EDL. In case that the Li ion batteries are unable to meet this criterion, a thermal battery (Li-$FeS_2$) is being used as in the case of Mars Pathfinder.

The Mars 2003 Sample Return / Athena Rover requires three batteries of 16 V (4 cells in each strings) and 6 Ah, connected in parallel, with a diode protection. The batteries will be provided with a heater to maintain temperatures of at least -30°C (minimum). Charging of the cells will be carried out at relatively higher temperature (0 to +30°C). A charge control unit, which includes individual cell monitoring and cell balancing circuitry control, is being developed in-house.

## 4.0 NASA/DOD JOINT EFFORT FOR Li ION BATTERIES

There is a considerable similarity in the needs of NASA and the Air Force for an advanced rechargeable lithium ion battery, especially for LEO/GEO satellites. Accordingly, a NASA/DoD Inter-agency consortium was recently initiated with the main intent of developing domestic capability to manufacture lithium-ion cells and batteries with smart chargers for both NASA and Airforce needs.[2] Under this program, multiple manufacturers are being supported to provide the desired technological developments. As a part of this program, various lithium ion cells, in both prismatic and cylindrical configuration, and with capacities ranging from 4 to 40 Ah, are being evaluated at JPL under generic performance conditions as well as those relevant to Mars 2001 Lander and 2003 Rover. In this paper, we report some of our recent observations from these on-going tests.

## 5.0 Li ION BATTERIES EVALUATION

The lithium ion cells evaluated contain proprietary electrolytes to achieve the desired low temperature performance and/or cycle life. It was deemed essential to keep the manufacturers anonymous to promote parallel development at each of the respective organizations. All the batteries have gone through a series of tests, aimed at establishing the baseline performance data of all the cells and validating lithium ion technology for the intended missions (Table 2). Accordingly, these tests consist of both generic and mission specific tests. The generic tests include cycle life at 100% DOD at ambient and low temperatures, and rate characterization at different rates (of charge and discharge) and temperatures ~~(Table 3)~~. Mission specific tests include cycling at partial depths of discharge and at alternating high and low temperatures, and accelerated and real-time cruise and mission simulation tests. The miscellaneous tests are aimed at understanding the thermal characteristics, temperature-compensated voltage charging, safety and failure modes.

**Li Ion Cells for Mars Lander/Rover Applications**

**Physical, Formation and EIS (impedance)**

| <u>Generic performance</u> | <u>Mission specific</u> | <u>Miscellaneous</u> |
|---|---|---|
| • Cycling at RT | • Cruise conditions | • V/T Charge |
| • Cycling at LT | • Cycling @ low DOD | • Thermal characteristics |
| • (Charge) rate vs. T | • Pyro-pulses | • DPA |
| • Discharge rate vs. T | • Cycling at different temperature | • Safety |
| • Self discharge | • Mission simulation | • EIS vs. Cycling |

Table 2. Description of tests being carried out on prototype lithium ion cells for Mars 2001 Lander and 2003 rover missions.

## 6.0 PRELIMINARY TEST DATA OF MARS 2001 LANDER AND 2003 ROVER CELLS

Large capacity (20 Ah) lithium ion cells were initially tested under this program[3] to examine the applicability of Li ion technology to both Lander and Rover missions. The performance of these cells has been encouraging, as evident from Figs. 2 & 3.

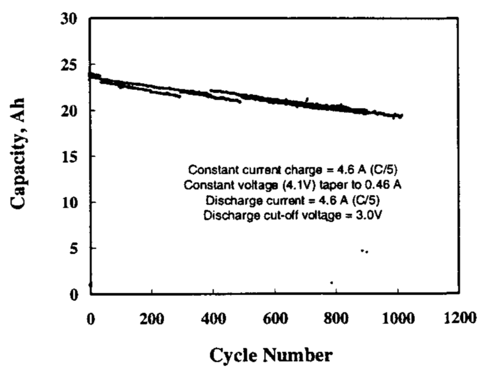


Fig. 2: Cycle life of 20 Ah Li ion cells at 25°C.

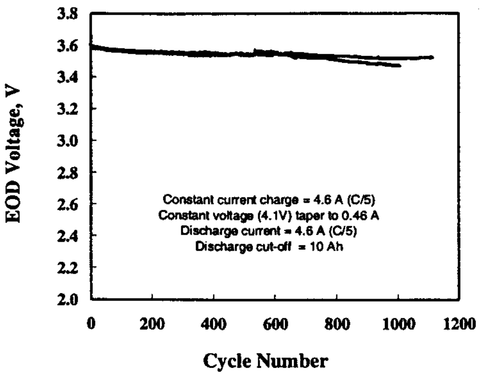


Fig. 3. End of discharge during partial-DOD cycling of 20 Ah Li ion cells at 0°C.

The cells displayed excellent capacity retention during 100% DOD cycling at room temperature (about 1000 cycles with a capacity fade rate 0.02% per cycle). At low temperature (0°C), the cells showed similar cycle life during partial (50%) DOD. In addition, the cells performed satisfactorily during high currents (60 A for 100 mS and 40 A for 60 s) pulses at all states of charge at 25°C. One deterrent factor for these early generation cells is a poor low temperature performance at sub-zero temperatures.

Subsequently, several improvements have been made in the technology of Li ion batteries, essentially to the electrolyte.[4,5] Similar approaches are being pursued at JPL.[6-8] Improved lithium ion prototype cells, thus received from different manufacturers show considerable improvements in the low temperature performance, without any noticeable penalty on the room temperature stability/cycle life. Figs. 4 and 5 show the capacity retention during (100% DOD) cycling at 25°C and -20°C, of Lander and Rover cells, respectively.

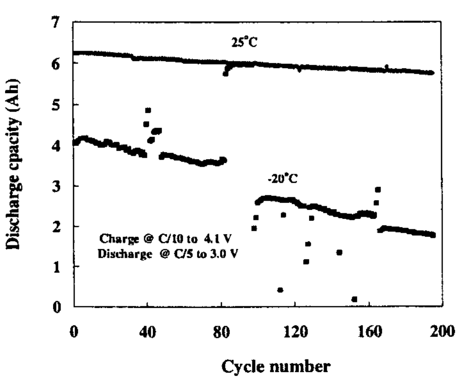


Fig. 4: Cycle life of Mars Lander Li ion cells at 25 and -20°C.

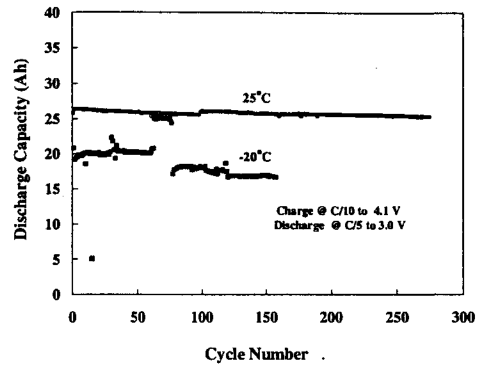


Fig. 5: Cycle life of Mars Lander Li ion cells at 25 and -20°C.

The cycle life, especially at low temperature, is encouraging and demonstrates the readiness of this technology for the Mars Lander and Rover missions.

## 7.0 ACKNOWLEDGEMENT

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